Adaptive M-QAM Modulation for MIMO Systems

Ramkumar Gowrishankar* and Mehmet Fatih Demirkol
University of Hawaii at Manoa, Honolulu, USA
{ramkumar, demirkol}@spectra.eng.hawaii.edu

I. INTRODUCTION

Adaptive modulation substantially increases the throughput of a wireless network by adjusting the modulation index to the channel conditions. It was shown in [1] that adaptive power and rate M-QAM system can give a power gain of almost 20dB relative to non-adaptive transmission for CDMA systems. A review of adaptive modulation for broadband system was presented in [2].

Multiple-input multiple-output (MIMO) links exploit the spatial dimension and antenna arrays at both ends of a link to transmit multiple parallel streams in the same time and frequency channel [3,4]. The result is an extraordinary bandwidth-efficient approach to wireless communication, especially in rich multi-path environments. V-BLAST [5,6] is a simple and widely considered architecture for open-loop (OL) MIMO systems.

Closed-loop (CL) MIMO systems feedback the channel state information (CSI) to the transmitter to set the antenna weights and transmit powers resulting in decoupled streams and greater capacity than OL-MIMO. The water-filling (WF) algorithm [4] maximizes the CL-MIMO capacity. A MMSE solution that minimizes the BER was proposed in [7]. CL-MIMO has not been favored because of the overhead in relaying the CSI to the transmitter. Although results with simulated channels based on Rayleigh-fading and Doppler models suggest otherwise, it was shown in [8] that if the statistical channel is replaced by more realistic indoor propagation channel model, CL-MIMO can be feasible despite the overhead in especially low-mobility indoor networks.

In this paper we propose algorithms for implementing adaptive M-QAM modulation for both OL- and CL-MIMO systems. The goal is to maximize the throughput subject to a target BER constraint. For OL-MIMO the algorithm proposed finds the number of transmit antennas and the modulation index to be used for all streams. For CL-MIMO, we propose a new rate maximization scheme that, on the average, has 20% throughput improvement over OL-MIMO. We also modify the water-filling and MMSE solutions to accommodate adaptive modulation and BER constraints. We use the flat Rayleigh-fading channel model for our simulations, and assume perfect channel estimation.

This paper is organized as follows: The OL- and CL-MIMO strategies are discussed in Section II. The adaptive M-QAM scheme is discussed in Section III. In Section IV we introduce our adaptive modulation implementations and propose a new rate maximization scheme for CL-MIMO that takes into account the BER threshold. Results and conclusions are presented Section V.

II. OPEN LOOP AND CLOSED LOOP MIMO STRATEGIES

A MIMO system uses multiple-element transmit and receive antennas to increase the data rate by exploiting the multipaths available. The general capacity formula is given by

0-7803-9068-7/05/$20.00 ©2005 IEEE

Report Documentation Page						*Form Approved* *OMB No. 0704-0188*

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
01 JAN 2005	**N/A**	**-**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Adaptive M-QAM Modulation for MIMO Systems	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Hawaii at Manoa, Honolulu, USA**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001846, Applied Computational Electromagnetics Society 2005 Journal, Newsletter, and Conference., The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**4**	

$$C = \max_{\mathbf{P}} \log_2 \left| \mathbf{I} + \mathbf{H}\mathbf{P}\mathbf{H}' \right|, \tag{1}$$

where **H** is the channel matrix and **P** is the (noise-normalized) transmit-signal correlation matrix. The noise-normalized total transmit power is given by with $P_T = trace\{\mathbf{P}\}$.

II.a Open-loop MIMO

In OL-MIMO links, no channel information is used at the transmitter. Each antenna transmits a different data stream with equal power. The V-BLAST system [5,6], employing successive interference cancellation (SIC) and zero forcing, is considered in this paper.

II.b Water-filling Solution

In CL-MIMO links, channel-dependent matrix transformations at the transmitter and receiver (determined by the sets of right and left singular vectors of **H**) decompose the matrix channel into a collection of uncoupled parallel channels. The water-filling algorithm [4] given below maximizes the capacity:

$$\alpha_i = \left(\mu - \frac{1}{\lambda_i} \right)^+, \quad \sum_i \alpha_i = P_T. \tag{2}$$

where λ_i is the i^{th} channel eigen-mode, α_i is the power allocated to the stream, μ is a Lagrange multiplier, and $(.)^+$ indicates that only non-negative values are acceptable.

II.c Closed-loop MMSE Strategy

An optimal solution for CL-MIMO links based on the mean-square error criterion is given in [7], with the power allocation strategy

$$\alpha_i = \left(\frac{\mu}{\sqrt{\lambda_i}} - \frac{1}{\lambda_i} \right)^+, \quad \sum_i \alpha_i = P_T. \tag{3}$$

This is also known as the inverse water-filling (IWF) because it allocates more power to the weaker streams in use to minimize the BER, in contrast to the water-filling solution.

III. ADAPTIVE MODULATION

Adaptive modulation increases the throughput of a wireless network by matching the transmission rate to the channel conditions. We consider square M-QAM adaptive modulation scheme. We adopt the approximations to the BER given in [9] as

$$BER \approx 0.2 \exp\left[-\frac{3}{2(M-1)} \frac{E_s}{N_o} \right], \tag{4}$$

where E_s is the symbol energy, N_o is the noise power and M is the modulation index. With γ as maximum tolerable BER, the modulation index for the i^{th} stream is obtained by rounding down

$$M_i = 1 - \frac{2}{3} \left(\frac{E_s}{N_o} \right)_i \frac{1}{\ln(5\gamma)} \tag{5}$$

to the nearest practical modulation index. The factor $(E_s/N_o)_i$ denotes the *SNR* of the i^{th} data stream.

IV. ADAPTIVE MODULATION FOR MIMO SYSTEMS

In this section we implement adaptive modulation for OL- and CL-MIMO systems and introduce a new closed loop rate maximization scheme that takes into account the target BER during calculation of the power allocation.

IV.a M-QAM based OL- MIMO System

With equal powers allocated to all transmit antennas and no transmit beamforming, the goal is to find how many streams (transmit antennas) and what modulation index can be employed using the given transmit power and the BER constraint. With the SIC algorithm, the receiver weights to detect a signal in the 1st layer, **w**, is minimum-norm row of the pseudo-inverse of **H**. If n_T transmit antennas are used, then the SNR of the first layer is

$$\frac{E_s}{N_o} = \frac{P_T}{n_T \|\mathbf{w}\|^2}, \tag{6}$$

Substituting (6) in (4) and using $M = 4$ (smallest QAM index) we find the largest value of n_T for the target BER. Once n_T is calculated, the modulation index is calculated using (5). Note that with SIC, the first layer has the worst BER; the successive layers are detected after canceling interference from detected streams. Thus looking at the first layer ensures that all streams (with the same modulation index) will satisfy the BER constraint.

IV.b M-QAM Based WF and IWF Solutions for CL-MIMO

The water filling and MMSE solutions maximize the capacity and minimize the BER, respectively. But both do not guarantee a target BER. The BER of each individual stream is different and if an average target BER is to be satisfied the stronger streams have to sacrifice their transmission rate in order to lower the BER. This makes both solutions unsuitable for adaptive modulation. In this section we propose a modification to both WF and IWF algorithms in order to maximize the throughput while maintaining a target BER.

The constraint in the WF and IWF strategies is that the Lagrange multiplier is accepted only if the power allocated to the weakest eigen-mode is greater than zero, i.e., $\alpha_i > 0$ where i is the weakest eigen-mode of the subset of eigen-modes being considered. We add the following constraint to satisfy the BER threshold for each stream:

$$\alpha_i \lambda_i > -\frac{9}{2} \ln(5\gamma) \tag{7}$$

This constraint makes sure that the weakest eigen mode can transmit at least QPSK for the given bit error rate threshold ensuring that the stronger streams need not sacrifice the transmission rate in order to maintain overall BER.

IV.c Rate Maximization Scheme

In this section we present a new rate maximization scheme that takes BER into account while calculating capacity. If adaptive modulation is used then the throughput is given by

$$C = \sum_i \log_2(M_i), \tag{8}$$

where M_i is the modulation index used for stream *i*. Substituting (5) in (8),

$$C = \sum_i \log_2\left(1 - \frac{2}{3\ln(5\gamma)} \alpha_i \lambda_i\right). \tag{9}$$

The power allocation strategy is found as

$$\alpha_i = \left(\mu - \frac{1}{\lambda_i} \frac{3\ln(5\gamma)}{2}\right)^+ \text{ s.t.} \begin{cases} \sum \alpha_i = P_t \\ \alpha_i \lambda_i > -\frac{9}{2}\ln(5\gamma) \end{cases}. \tag{10}$$

V. RESULTS AND CONCLUSION

Figures 1 and 2 show the average throughput and average number of streams used vs. SNR, respectively. All simulations assume a target BER of 10^{-2} and a 4x4 system. It can be seen that above 20dB the rate maximization and modified WF have greater throughput than IWF and OL-MIMO. This is because the two schemes adopt a more conservative approach in allocating power to the streams and hence the stronger streams can take better advantage of adaptive modulation. On an average they show 20% improvement over open loop and 14% improvement over the IWF. In the 5 to 10 dB range, all schemes have almost identical throughput because the number of streams allocated by all the schemes are similar and the SNR is not high enough to take advantage of adaptive modulation. In the 0 to 5 dB range the throughput of closed loop is better than open loop because it is able to take advantage of the channel conditions.

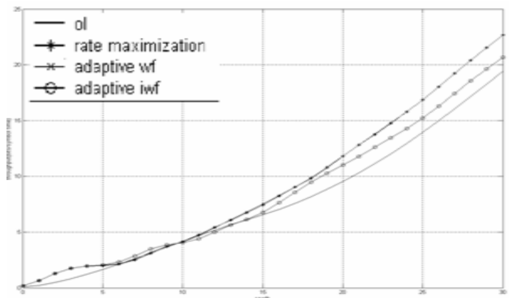

Fig. 1 Throughput of the 4 schemes discussed in section IV. The x-axis is SNR and y-axis is the throughput per symbol time.

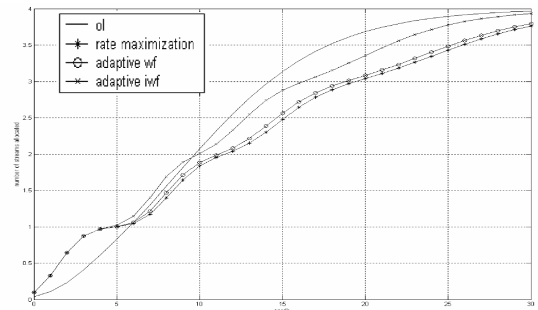

Fig. 2 Average number of streams used by the 4 schemes plotted for varying SNR. The system has 4 transmit and 4 receive antennas

A new adaptive MQAM modulation based rate maximization algorithm was developed for CL-MIMO and V-BLAST algorithm was modified for OL-MIMO systems. Compared to the OL-MIMO system, the new rate-adaptive closed-loop system showed a throughput improvement of almost 20% at 20dB and above. When seen in conjunction with results in [8], we conclude that CL-MIMO is a practical option for indoor high speed wireless networks. Further research issues include investigation of scheduling based on channel conditions in addition to conventional issues and studying effects of interfering MIMO links when adaptive modulation is used.

REFERENCES

[1] A. J. Goldsmith and S. Chua, “Variable-rate variable-power MQAM for fading channels,” *IEEE Trans. Comm.*, vol. 45, pp. 1218-1230, Oct. 1997.

[2] S. Catreux, V. Erceg, D. Gesbert, R. W. Heath, Jr., “Adaptive modulation and MIMO coding for broadband data networks,” *IEEE Comm. Magazine,* vol. 40, no. 6, June 2002.

[3] G. J. Foschini, M. J. Gans, “On limits of wireless communications in a fading environment when using multiple antennas,” *Wireless Personal Comm.*, vol. 6, 1998.

[4] E. Telatar, “Capacity of multi-antenna gaussian channels,” *Technical Report, AT&T Bell Labs*, June 1995.

[5] G. D. Golden, G. J. Foschini, R. A. Valenzuela, P. W. Wolniansky, “V-BLAST: an architecture for realizing very high data rates over the rich-scattering wireless channel,” *Int’l Symp. on Signals, Systems and Electronics*, pp. 295-300, Sep. 1998.

[6] G. D. Golden, G. J. Foschini, R. A. Valenzuela, and P. W. Wolniansky, “Detection algorithm and initial laboratory results using V-BLAST space-time communication architecture,” *Electronics Letters*, vol. 35, no. 1, Jan. 1999.

[7] H. Sampath, A .J. Paulraj, “Joint transmit and receive optimization for high data rate wireless communication using multiple antennas,” *Proc. of the Asilomar Conference on Signals, Systems, and Computers*, vol. 1, pp. 215–219, Oct. 1999.

[8] M. F. Demirkol, M. A. Ingram, Z. Yun, “Feasibility of closed loop operation for MIMO links with MIMO interference,” *Proc. of the IEEE Int’l Symp. on Antennas and Prop.*, Jun. 2004.

[9] S. Zhou, G. B. Giannakis, “Adaptive modulation for multi-antenna transmissions with channel mean feedback”, *IEEE Trans. on Wireless Comm.*, vol. 3, no. 5, Sep. 2004.